The reverse guillotine tribometer for evaluation of sliding wear of Additive Manufactured fixtures

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Abstract
Purpose – The purpose of this paper is to present a custom-built tribometer that mimics the wear of additive manufactured fixtures used in inspection of sheet metal components.
Design/methodology/approach – Referring to the inspection of sheet metal parts, the fixture undergoes sliding wear during loading and unloading phases of the quality control operation. A new wear test is proposed to mimic the actual wearing conditions of the fixtures because the standards are deemed insufficient. In the tribometer, a cylindrical Alumide cantilever beam is made to slide back and forth inside a slightly bigger hole cut into a nickel-plated steel sheet. The sheet is spring loaded such that it applies a force on the specimen. The wear on the beam is measured after every 500 cycles of the beam motion.
Findings – Results of some first test trials are reported to evaluate the durability of Alumide fixtures fabricated by selective laser sintering. The results are also compared to those obtained for a machined fixture made of an Al-Cu alloy.
Practical implications – The proposed wear test estimates the life time of additive manufactured fixtures in terms of numbers of inspected components. The test can be extended to different materials to compare their durability.
Originality/value – Today, the fabrication of custom fixtures by means of additive manufacturing technologies is a reality in many manufacturing industries. The advantage of using those production technologies for custom fixtures is well assessed in literature in terms of manufacturing times and costs, whereas little attention was given to the life time and wear behaviour of fabricated fixtures. For its practical implication, the fixture durability is indeed very important for manufactures.

Keywords Selective laser sintering, Rapid manufacturing, Sliding wear, Alumide, Custom fixtures

Paper type Research paper

1. Introduction

Fixtures play a key role in the pursuit of high quality standards in manufacturing. They are used to align and hold accurately and securely a component or a sub-assembly during different operations (machining, assembling, welding, inspection, testing, etc.) along the manufacturing cycle.

Generally, several different fixtures are designed for the same component, because each operation has some specific locating and holding requirements. Since fixturing cost can account for up to 20 per cent of the total cost of a manufacturing system (Bi and Zhang, 2001), the use of dedicated fixtures, that are specifically designed for one component, is justified only in mass production. When the manufacturing volumes decrease, general purpose modular fixtures are used because of their flexibility. Modular fixtures can be arranged in different combinations, because fixture elements are interchangeable. Thus, several configuration of the fixture are possible. Modular fixtures are ideal for intermittent or one-time use, especially in the case of low volume productions wherein the cost of the fixture cannot be amortized over a large number of parts. Over the past decades, the attention of researchers was driven to define iterative, semi-automated and automated procedures to ease the design of fixtures with the aid of the computer (Alarcon *et al.*, 2010; Boyle *et al.*, 2011; Li *et al.*, 2002; Peng *et al.*, 2009, 2010; Ryll *et al.*, 2008; Wang *et al.*, 2010; Wu *et al.*, 2008; Zheng and Chew, 2010).

Referring to quality control operations, the fixture does not undergo high stresses, because great clamping forces are not required. For instance, during pointwise measurements performed on a coordinate measuring machine (CMM), the part is subjected to very low contact forces and it is not placed in hostile environment.

Recently the use of tailored fixture for the inspection of products has become imperative to keep up with the increase in complexity of geometries and shapes that designers create to enhance the aesthetical attractiveness. Generally, custom fixtures are fabricated by traditional milling processes when their shape is simple. On the contrary, the use of additive manufacturing (AM)

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techniques is particularly worthwhile when the complexity of the custom element increase. In the industrial field, the fabrication of custom fixtures was historically one of the first applications of rapid prototyping (RP) technologies for end-product manufacturing (Violante *et al.*, 2007). Materialise was the pioneer with the release of RapidFit, a fixture design software to combine tailored elements with modular bases and beams. After importing the solid to layer (STL) file of the part to be inspected into RapidFit software, the definition of the fixture is quite simple. First of all the base plate of the modular fixture is inserted. Then the position of a supporting element can be easily selected by clicking on the desired contact zone on the part surface. In that location, RapidFit software generates automatically the custom element tuning it to the part geometry (Figure 1). Standard beams can be mounted between the base plate and the RapidFit fixture in order to reduce the length or the height of the custom element to be manufactured. The extent of the contact zone of the custom element can be adjusted, but it is not a single point, so the part weight or load is distributed over a certain area reducing contact pressure and deformations (Figure 2).

Aside from this aspect, the fabrication of AM tailored fixtures brings other undeniable advantages. Any desired shape can be produced, since layer by layer manufacturing is free from any geometrical constraint. The only limitation is related with the overall dimensions of the part that cannot exceed the building volume of the RP machine. Commonly tailored fixture elements to be combined with modular standard fixtures have a small size, so several different custom elements are fabricated at one job.

Second, unlike traditional machining, additive fabrication does not require any tooling, any tool-path computation and no scrap is produced. The overall manufacturing time and cost are reduced as well as the ecological footprint.

Finally the cost of the AM custom elements is not influenced by the complexity of the element geometry. The cost depends only on the material used and on the building time of the RP machine (some hours). For applications in the automotive sector, it was proven that using AM tailored elements costs can be reduced up to 66 per cent, while the fixture lead time is almost cut by half (Eyers *et al.*, 2009).

AM tailored elements are mainly made of plastic materials, but the fabrication from metal powders by selective laser sintering (SLS) or selective laser melting (SLM) is a reality today. Almost all the literature about RapidFit fixtures is focused on savings related to production times and costs (Eyers and Dotchev, 2010; Eyers *et al.*, 2009). Almost no attention was given to their durability, while there is a great interest for comparing the life of plastic fixture elements with the one of machined metal fixtures.

As regards inspection applications, friction helps a fixture to hold the inspected part without the use of a clamping system. On one hand the loading and unloading operations are faster because no clamping device has to be operated. On the other hand, as a consequence of friction, fixtures undergo wear during part loading and unloading and after some time the AM custom elements have to be replaced. The life time of an element depends of course on its material. An interesting plastic base material available only for AM is Alumide, an aluminium-filled polyamide 12 powder, which is characterised by its high stiffness and higher heat resistance than regular plastics. Alumide has a metallic grey colour and good post processing possibilities, so the fixtures can be refined very easily by grinding, polishing or coating. The machining of Alumide laser-sintered parts is simplified through the cut breaking effect of the aluminium filling.

The aim of this work is to evaluate the durability of Alumide fixtures assessing it in terms of number of inspected sheet metal parts. To this purpose, a specific wear test is proposed and a custom tribometer was designed to resemble the real wearing conditions on an Alumide fixturing element with a standard geometry. Using the apparatus, an AM fixture element is subjected to repeated blocks of sliding cycles through contact with a hole in a small sheet metal part. After each repetition, wear is evaluated by measuring the size reduction of the Alumide specimen by means of a CMM. The test was also extended to a second specimen, that was fabricated of an Al-Cu alloy by traditional machining technologies. In such a way a comparison of the durability of the two materials was possible.

2. Materials and methods

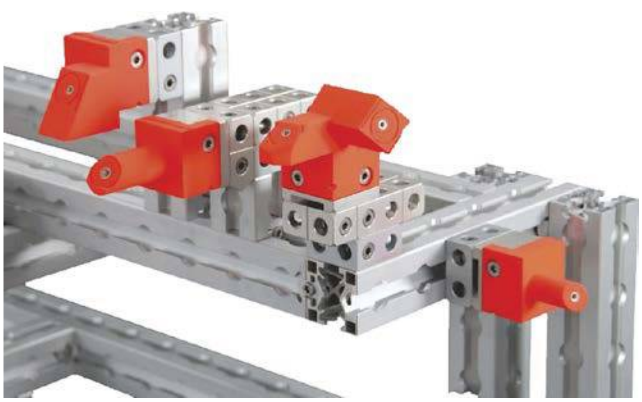
2.1 Standard wear test methods

Wear test methods are aimed at testing different types of wear in different conditions for a specific material. In the case of plastic materials, standard methods for sliding wear evaluation are of the type block-on-ring (ASTM G137-97 and ASTM G176-03). Other methods, not specific for plastics are the pin-on-disk (ASTM G99-05) and the reciprocating sliding (ASTM G133-05).

As regards polymers and polymer composites in general, the influence of contact conditions is explained in several works (Axen and Hutchings, 1996; Briscoe and Sinha, 2002; Friedrich and Reinicke, 1998; Friedrich *et al.*, 2002, 2005; Hutchings, 2001).

Figure 1 Examples of tailored AM fixtures matching part feature

Figure 2 Modular fixture with AM custom elements



To the authors' knowledge, tribological aspects of additive manufactured plastic parts are not extensively documented in technical literature. The limited wear resistance of plastic materials and prototypes is likely the reason. Nevertheless, some authors (Equbal *et al.*, 2010) have used the pin-on-disk method to analyse the wear behaviour of ABS plastic parts fabricated by fused deposition modelling (FDM). Much more attention was dedicated to the wear behaviour of additive manufactured metal parts (Colaco and Vilar, 2005; Kumar, 2009; Ramesh and Srinivas, 2009; Ramesh *et al.*, 2009; Sebestyen *et al.*, 2005; Sevidova *et al.*, 2008; Takacs *et al.*, 2004) because of their higher resistance and wide range of application.

However, ASTM standard wear tests are not representative of the real wearing conditions of the fixture, because they do not simulate the real process sufficiently well. The definition of a specific wear test is allowed in this case because the standards are deemed insufficient (Blau and Budinski, 1999).

When a sheet metal part is loaded (and unloaded) on the supporting fixture for inspection, the AM elements undergo uniaxial sliding wear in the contact zone with the part. The contact surface is very small, because normally the contact area is the lateral wall of a circular or shaped hole of the sheet metal whose thickness is limited to a few millimetres. The allowance between the fixturing element and the part feature has to be tight. The fabrication accuracy of the AM techniques can be as high as 0.05 mm and the custom element can be manually further adjusted and finished to fit. The friction force is generally low because it is related with the component of the part weight distributed on the single fixture and sheet metal parts are rather light.

In addition to this, it is difficult to express or convert the result of a standard wear test in terms of number of inspected parts. Such a number is useful to evaluate the life time of the fixture in order to forecast when the custom element should be substituted because of excessive wear, that compromises the fixture repeatability as well.

Thus, a custom tribometer was designed for a specific wear test, aiming to evaluate the life time and durability of AM custom fixtures in terms of number of inspected components. The proposed test and apparatus mimic the load/unload cycle of the sheet metal on the fixturing element under operating conditions similar to the real ones.

2.2 Custom built tribometer

In the specific wear test, the AM fixture element should undergo uniaxial sliding wear in the contact zone with the mating feature of the sheet metal part. The apparatus provides an alternating uniaxial motion to an AM specimen that slides inside a hole located in a sheet metal part. The part is constantly kept in contact with the AM element by means of a spring.

A commercial OWIS Limes 122 motorized positioning system with a step motor was selected to move the AM specimen during the test. The OWIS linear stage is placed horizontally on the working table and an L-shaped support is connected to its carriage. In this way, an alternating uniaxial horizontal motion is provided to the specimen that is mounted on the L-shaped support (Figure 3).

The tribometer is then completed by a vertical device made of steel that was named "reverse-guillotine" (Figure 4). The reverse-guillotine consists of a base which is connected to the OWIS linear stage and two vertical guides for the guillotine. The guillotine is a small block that is limited to move vertically by its two side wings that are inserted into the grooves of the vertical guides. A traverse is placed at the top of the vertical guides and the guillotine is connected to it by means of a spring. When the spring

Figure 3 Custom built tribometer for wear testing of AM fixtures

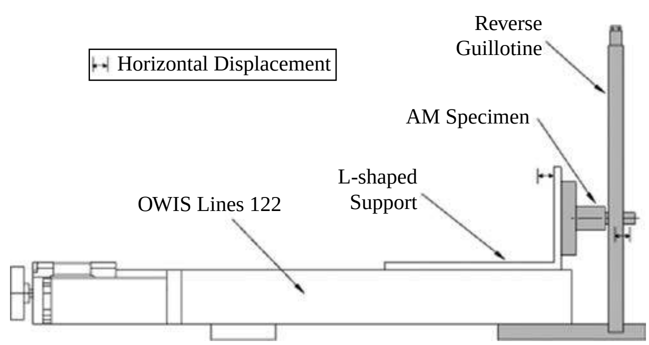
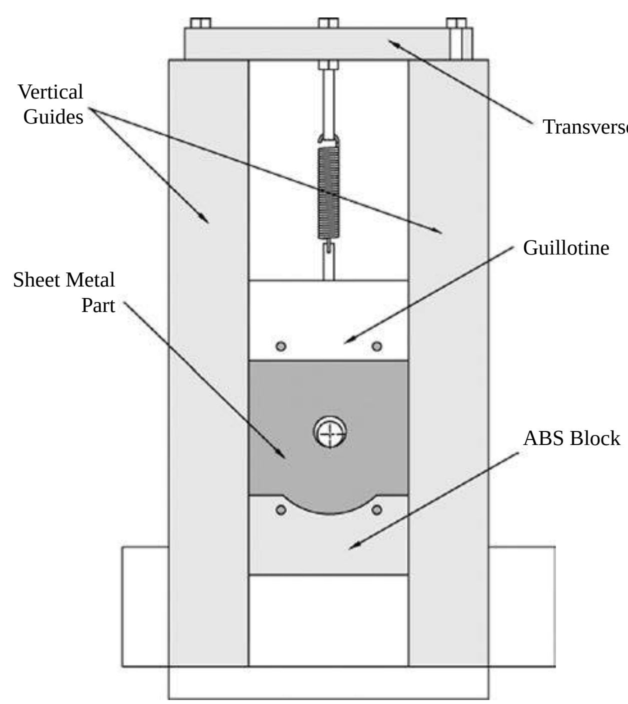


Figure 4 Detail of the reverse-guillotine



is extended from its unstretched position, it forces the guillotine to move upwards. This is the reason why the vertical device is called “reverse-guillotine”: a guillotine normally moves downwards. A sample of a sheet metal part is mounted on the guillotine, so the spring is used during the wear test to keep the sheet metal part constantly in contact with the specimen.

The spring was dimensioned to apply a low contact force to the specimen. An extension spring with German hooks was used. It has a wire diameter of 0.80 mm, an external diameter of 6.40 mm, a free length of 36.40 mm and a rigidity of 0.59 N/mm.

An additional guiding block manufactured by FDM of ABS (i.e. Acrylonitrile butadiene styrene) material completes the reverse-guillotine system. The ABS block is connected to the lower border of the sheet metal part and has two wings that are inserted into the grooves of the vertical guides. Together with the guillotine, it constraints the sheet metal part during the test preventing vibrations. The overall dimensions of the tribometer are 420 mm × 210 mm × 135 mm (length × width × height).

The Alumide specimen is securely mounted on the L-shaped support of the OWIS linear stage. The stage is manually moved forward towards the reverse-guillotine until the length of pin is centred through the hole of the sheet metal part. During this operation the spring is extended 1 mm to keep the sheet metal in contact with the lower part of the pin.

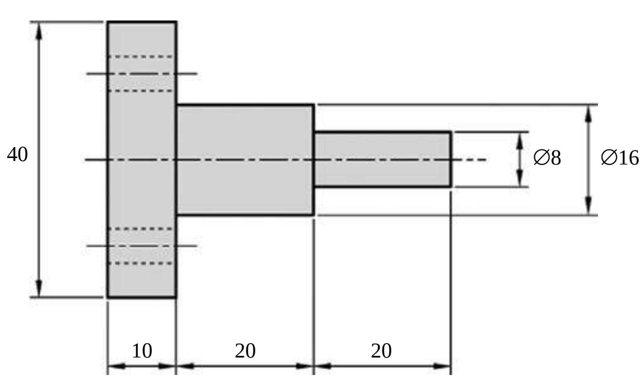
This means that the sheet metal part applies a force of 0.59 N to the specimen pin because of the spring stretching.

Second, the OWIS stage is actioned to travel automatically 5 mm forward, then 10 mm backward and again 5 mm forward to complete one wearing cycle at a linear speed of 0.60 m/min. Under these conditions, for the ABS specimen each cycle represents one loading and unloading operation of the sheet metal part on the supporting fixtures.

2.3 Test specimen

The AM specimen for the wear test was designed referring to a typical RapidFit custom element. A RapidFit fixture has a square base to connect it to a modular beam. The specimen has a square base with four holes to connect it to the L-shaped support mounted on the OWIS stage. The custom geometry of a generic RapidFit fixture was simplified to a cylinder, which is a measurable shape allowing for wear evaluation in a simple way. A 20 mm long round pin of 8 mm in diameter was used. A supporting cylinder 16 mm in diameter and 20 mm in height was inserted between the square base and the pin (Figure 5). It should be remarked that only the 8 mm round pin will be subjected to the wear test, because it resemble the tailored end part of the Rapidfit fixture that locally matches the sheet metal part.

Figure 5 Geometry of the AM specimen



Six specimens of Alumide material were fabricated by SLS on a P395 EOS machine. They were manufactured with a layer thickness of 0.15 mm in about 3 hours and a half.

The properties of Alumide material are listed in Table I. They were extracted from EOS database of proprietary materials for SLS.

1 mm thick zinc-plated HCT500X steel sheets with a 10 mm hole were used as samples of the sheet metal part to be inspected. The hole was drilled with a 9.5 mm drill and then finished with an H7 reamer. The sheet metal specimen is 50 mm high and 30 mm long. The hole is centered on it and the specimen is connected to the reverse guillotine and the ABS block by means of four small threaded pins. A diameter larger than the one of the specimen pin was adopted for the hole, so that the contact between the specimen and sheet metal part is limited to a specific zone located in the lower half of the pin surface. The hole was drilled in the sheet metal, so its edges are quite sharp.

2.4 Methodology

Before starting the wear test, the unworn specimen geometry was assessed by pointwise measurements performed on a CMM and by scanning the pin surface by a contact trigger probe. In order to have an unaltered reference for next comparisons, it was decided to limit the wear test to a length of 10 mm centred on the pin height. Therefore, the two ends of the 8 mm are maintained unworn and do not undergo the wearing phenomenon.

The unworn specimen geometry was assessed by the CMM through measuring the pin diameter in the middle of the height was measured on seven sections evenly spaced every 2 mm in the zone of the wear test (Figure 6a).

The origin of the Cartesian reference system during the part alignment on the CMM was set at the centre of the top face of the pin. The *Z*-axis was aligned with the specimen symmetry axis and the seven sections were positioned at the following Z levels: -4, -6, -8, -10, -12, -14 and -16 mm. With such a reference system, the wear test zone extends from $Z = -5$ mm to $Z = -15$ mm. This means that the diameter of the first section ($Z = -4$ mm) and the one of the last section ($Z = -16$ mm) were measured outside the worn area.

In each section the pin diameter was measured by 16 points (Figure 6(b)). Five points are located in the upper half of the pin and are evenly spaced on the semi-circle every 45 degrees. The others are located on the lower half and are evenly spaced every 15 degrees. Thereby the point density is increased in the wear test zone to evaluate and monitor diameter changes owing to the pin consumption.

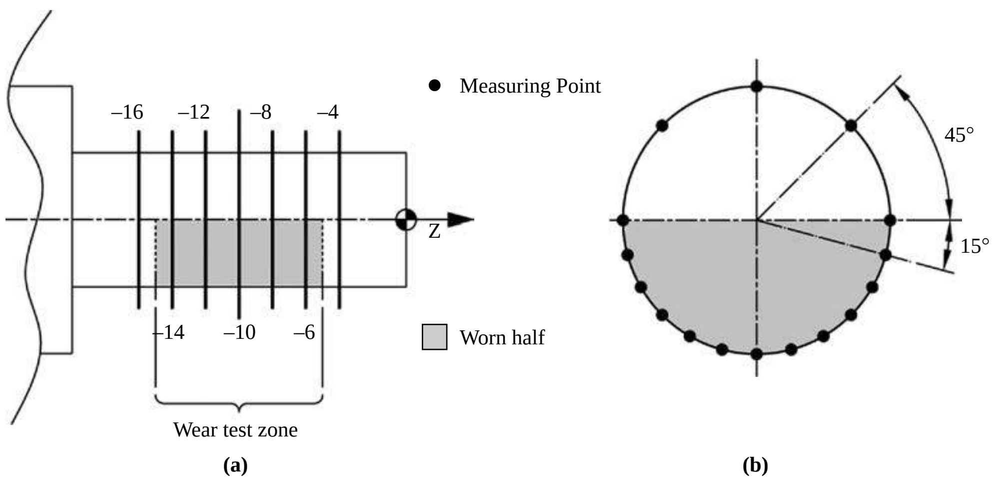
A more extensive and detailed analysis of the pin surface is carried out by a contact digitiser. The scan area is properly set to cover the whole surface of the pin half undergoing wearing plus a portion of the supporting cylinder 16 mm in diameter. The stair step between the two cylinders is used as reference in the next comparative analysis of scan data.

After assessing the pin geometry in the unworn state (zero wearing cycles), several wearing cycles were repeated and after every 500 cycles the pin diameter was measured again by the CMM by using the same measurement strategy described afore. Since measurement fixtures are important aspects of the quality assurance of a product, in order to estimate the life time of the fixture, the maximum wear limit of the pin diameter was set to 0.10 mm. Normally a minimum of four fixtures is used Markenscoff *et al.* (1990), so an increase in the play of 0.10 mm on each fixture compromises the replicability

Table I Different properties of Alumide material

Property	Value	Unit	Test standard
Tensile modulus	3,800	MPa	ISO 527-1/-2
Tensile strength	48	MPa	ISO 527-1/-2
Strain at break	4	%	ISO 527-1/-2
Charpy impact strength (+23°C)	29	kJ/m^2	ISO 179/1eU
Charpy notched impact strength (+23°C)	4.6	kJ/m^2	ISO 179/1eA
Flexural modulus (+23°C)	3,600	MPa	ISO 178
Flexural strength	72	MPa	ISO 178
Shore D hardness (15 s)	76	–	ISO 868
Melting temperature (10°C/min)	176	°C	ISO 11357-1/-3
Vicat softening temperature (50°C/h 50 N)	169	°C	ISO 306
Density (lasersintered)	1,360	kg/m^3	EOS method

Figure 6 Measurement strategy for evaluating pin diameter: location of the seven cross sections (a), location of the measured points on each cross section (b)



of fixturing and positioning during inspection. For this reason, blocks of 500 wearing cycles and subsequent CMM measurements were repeated until the diametral wear exceeds 0.10 mm, and then the wear test was over.

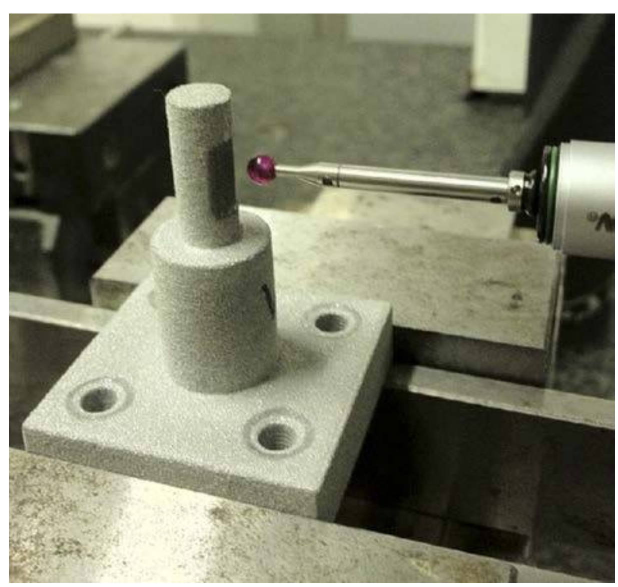
3. Results

As a first essay of the wearing test carried out by means of the reverse-guillotine, the results are presented for one of the six Alumide specimens. There was no difference in the production process: the same SLS parameters and layer build direction was used, so theoretically the specimens are identical. Nevertheless, because of SLS process tolerances, the actual pin geometry of every specimen as fabricated will differently differ from the one of the STL model. Thus, the unworn pin geometry was assessed by a preliminary measuring phase on the CMM before starting the wear test.

3.1 CMM measurements

The selected specimen was inspected by a probe tip of 3 mm on a DEA CMM model GLOBAL image 07.07.07, that is equipped with an indexable swinging head and a touch trigger probe (Figure 7). The volumetric length measuring uncertainty MPE

Figure 7 Pointwise measurements of the Alumide specimen by means of the CMM



of the machine according to ISO-10360/2 is $1.5 + L/333\,\mu$m, where MPE is the acronym for maximum permissible error and L is the measured length. The pointwise measurements of the specimen were replicated three times at each measuring phase. The results of the measurements replication for the unworn specimen are listed in Table II. For each of the seven sections, the average pin diameter was computed as mean value of the three replications. Considering the t distribution with two degrees of freedom, the 95 per cent confidence intervals are also indicated.

Then the wear test was started and measurements were repeated every 500 wearing cycles. An example of the results of worn pin measurements is shown in Table III for the specimen after 2,000 wearing cycles.

3.2 Evaluation of diametral wear

After every 500 cycles, for each of the seven sections the diametral wear of the pin was computed as the difference between the average value of the initial unworn diameter and the one of the current diameter. An example is given in Table IV for wear evaluation on the Alumide specimen after 2,000 cycles.

In order to have a unique reference value for the pin wear at each number of wearing cycles, the average wear of the pin was evaluated by the mean value of the diametral wear of the five sections that are inside the worn zone. The external sections located at the positions $Z = -4$ mm and $Z = -16$ mm were not considered because they are not sensibly affected by material consumption.

For instance, the average wear of the specimen at 2,000 cycles is 0.052 mm, that is the mean of the values from the second to the sixth row in the diametral wear column of Table IV.

Another specimen was fabricated of an Al-Cu alloy (commercial grade AA2024, also known as duraluminium) by traditional metal cutting on a turning machine. The AA2024 alloy was chosen for its great machinability. The wear test was repeated for the duralumium specimen by using the same methodology that was described for the Alumide material.

The evolution of the average wear at different numbers of cycles for the two specimens is plotted in the graph of Figure 8.

The graph shows that the wear behaviour of the two materials is very similar. The average diametral wear of the Alumide pin at 5,500 cycles exceeds the defined limit of 0.10 mm. The same limit is reached by the machined AA2024 specimen for a slightly smaller number of cycles ranging from 4,500 to 5,000. Since only one specimen of each material was tested for this preliminary study, by considering a safe margin related to the material variability it can be estimated that the two materials have almost the same durability. The following discussion will focus on the Alumide specimen, since the AM fixtures are the object of this study.

4. Discussion

For the slope of the evolution profile in Figure 8, it can be observed that the rate at which the average diametral wear grows is higher at the beginning of the test and progressively decreases as the test goes on. This is not surprising since the contact area between the hole of the sheet metal part and the specimen pin is very small when the test starts. Thus, the contact force is spread over a small area and a high pressure is applied to the most superficial layers of Alumide material. Predominantly delamination wear is observed on the surface of the specimen during the earliest cycles. Evidence of the pin consumption with delamination of the most superficial layers of the specimen is shown in Figure 9.

As the test goes on and the number of wearing cycle grows, owing to the pin consumption, the contact area between the hole of the sheet metal part and the pin increases and the contact force generates a lower pressure. This behaviour justifies the change of the wearing rate during the test.

Table II Results of the measurements of the specimen at 0 cycles (unworn pin)

Pin section	Diameter (mm) Meas. 1	Meas. 2	Meas. 3	Average (mm)	95% confidence interval (mm)
$Z = -4$ mm	8.011	8.012	8.008	8.010	7.992-8.010
$Z = -6$ mm	7.998	7.996	7.996	7.997	7.988-8.006
$Z = -8$ mm	7.986	7.982	7.982	7.983	7.974-7.992
$Z = -10$ mm	7.990	7.987	7.986	7.988	7.979-7.997
$Z = -12$ mm	7.975	7.972	7.970	7.972	7.963-7.981
$Z = -14$ mm	7.961	7.958	7.957	7.959	7.950-7.968
$Z = -16$ mm	7.978	7.973	7.973	7.975	7.962-7.988

Table III Results of the measurements of the Alumide specimen after 2,000 wearing cycles

Pin section	Diameter (mm) Meas. 1	Meas. 2	Meas. 3	Average (mm)	95% confidence interval (mm)
$Z = -4$ mm	8.003	8.001	8.000	8.001	7.997-8.005
$Z = -6$ mm	7.987	7.984	7.982	7.984	7.975-7.993
$Z = -8$ mm	7.926	7.924	7.924	7.925	7.921-7.929
$Z = -10$ mm	7.925	7.924	7.923	7.924	7.920-7.928
$Z = -12$ mm	7.915	7.913	7.913	7.914	7.910-7.918
$Z = -14$ mm	7.890	7.889	7.889	7.890	7.886-7.894
$Z = -16$ mm	7.971	7.969	7.968	7.970	7.961-7.979

Table IV Results of wear evaluation for the Alumide specimen after 2,000 cycles

Pin section	Average diameter (mm) 0 cycles	2,000 cycles	Diametral wear (mm)	Mean value (mm)
Z = −4 mm	8.010	8.001	0.009	
Z = −6 mm	7.997	7.984	0.013	
Z = −8 mm	7.983	7.925	0.058	
Z = −10 mm	7.988	7.924	0.062	0.052
Z = −12 mm	7.972	7.914	0.058	
Z = −14 mm	7.959	7.890	0.069	
Z = −16 mm	7.975	7.970	0.005	

Figure 8 Evolution of average diametral wear of the pin at different numbers of wearing cycles

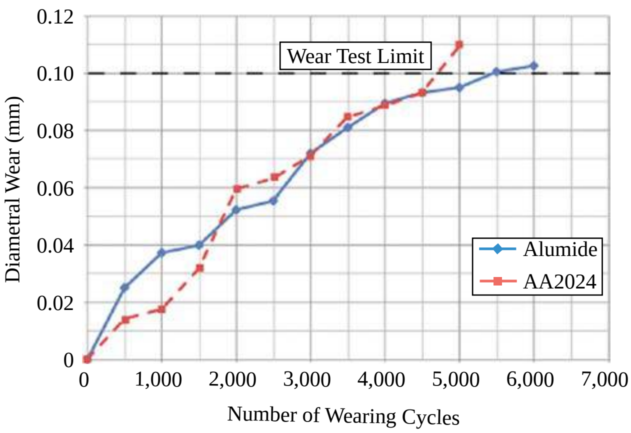


Figure 9 Evidence of delamination wear at the earliest stages of the wearing test of the Alumide specimen

Fine alumide powder is generated during sliding. The powder normally drops down by gravity and stops on the additional guiding block made of ABS. Presence of the Alumide powder can be seen in the middle of the lower border of Figure 9. The powder does not stick to the border of the hole on the metal part and Alumide-Alumide contact was not detected. The heat generated during the test is negligible since Alumide material is predominantly made of nylon plastics.

It is also possible to plot a rough profile of the pin geometry at a specific number of wearing cycles by plotting the value of the average diameter of each section versus its Z level or position. An idea of the pin consumption and variation of the diameter of each section can be visualized by superposing the profiles of the pin geometry corresponding to different numbers of cycles (Figure 10).

The vertical dashed lines in Figure 10 represent the limits of the wear zone, which ranges from Z = −5 mm to Z = −15 mm. The profile referring to 4,000 wearing cycles is omitted to increase the readability of the figure. It can be noticed that the value of the diameter of the two sections located outside the wear area does not changes significantly with the number of wearing cycles. This is not unexpected, since the two sections lie outside the wear zone and should not undergo wearing during the test.

At a first glance, it seems that the profiles of the pin geometry in the wearing zone remain almost parallel as the number of wearing cycles increases (Figure 10). Nevertheless, a good observer may notice that wearing appears a little bit greater for those sections on the left that are inside the worn area and nearer to the supporting cylinder of 16 mm. The Alumide material consumption over the seven cross section can be estimated by means of the integrity ratio. Considering for each cross section the final diameter of the pin at the end of the test and the one at the beginning of the test, the integrity can be defined as the ratio of the final pin diameter to the initial pin diameter.

The values of the integrity ratio of Table V confirm that material consumption progressively increases as the section is closer to the supporting cylinder of 16 mm. This fact suggests that during a wearing cycle the pin behaves like a cantilever supported only on the side of the 16 mm cylinder. The contact force imposed by the spring to the sheet metal part causes the pin bending. The bending moment and the consequent deflection are larger for sections that are far from the fixed end of the pin. As wear cycles increase, the material consumption grows and the pin cross section decreases.

Figure 10 Profiles of Alumide pin geometry at a different numbers of wearing cycles

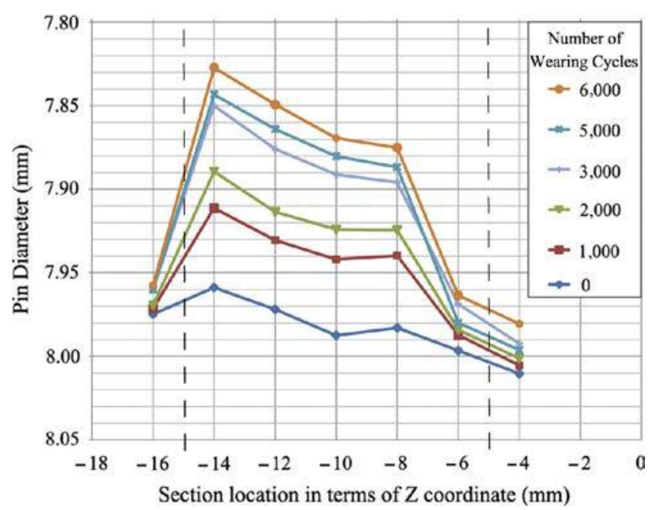


Table V Comparison of the Alumide material consumption over the seven cross sections

Pin section	Average diameter (mm) Final (6,000 cycles)	Initial (0 cycles)	Integrity ratio % (D final/D initial)
Z = −4 mm	7.981	8.010	99.63
Z = −6 mm	7.964	7.997	99.59
Z = −8 mm	7.875	7.983	98.65
Z = −10 mm	7.870	7.988	98.52
Z = −12 mm	7.849	7.972	98.46
Z = −14 mm	7.827	7.959	98.35
Z = −16 mm	7.958	7.975	99.78

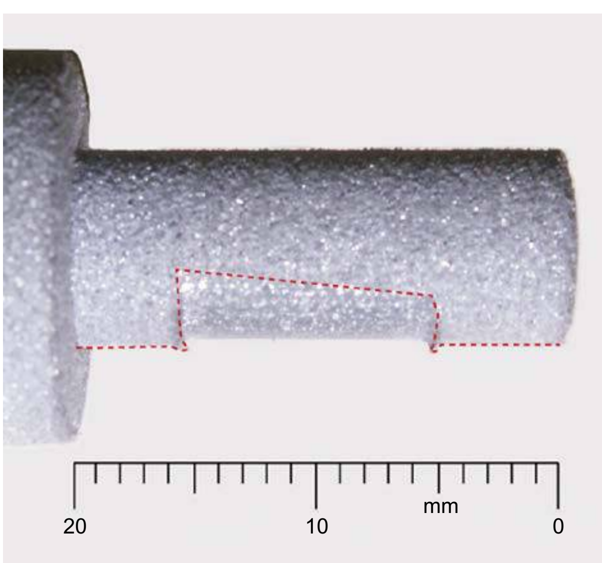
Thus, the bending resistance of the pin is lower and the higher deflection restraints the material consumption because the pin bends away from the hole.

Deflection is partially compensated by the action of the spring and is allowed by the 2 mm play between the dimension of the pin (8 mm) and the one of the hole (10 mm).

Finally it is important to observe that the consumption of the section located at Z = −6 mm is very small and its integrity ratio is very close to the one of the extreme sections located outside the worn area. This result cannot be justified by taking into consideration the cantilever-bending behaviour alone. In addition to this, from Figure 10, for that specific section it can be detected that the value of the diameter after 5,000 wearing cycles is greater than that at 3,000 wearing cycles. As a consequence of the sliding action, the Alumide material of the specimen is consumed and removed. However, due to its plasticity, it also partially flows to the ends of the wear zone, because it is deformed by the sheet metal part and pushed ahead in the sliding direction. The plastic deformation is responsible for the enlargement of the pin diameter in that specific section and in the two sections which lie outside the wear zone. The material consumption is predominant and the plastic deformation can be disregarded inside the wear area.

A photograph of the side view of the pin after 6,000 wearing cycles is shown in Figure 11. The dashed line indicates the contour of the worn area of the pin and reminds the

Figure 11 Alumide pin surface after 6,000 wearing cycles



profiles of Figure 10. Owing to the sliding contact with the steel of the sheet metal, the Aluminium grains appear glossier on the worn material and the pin surface is smoother.

Figure 11 illustrates the evidence of both cantilever-bending behaviour and plastic deformation. As a consequence of the first phenomenon, the contact zone between the sheet metal part and the pin is greater for those sections that are closer to the supporting cylinder of 16 mm. For this reason the border of the worn area is not parallel to the generating line of the cylinder. In the projected top view, the worn area does not appear rectangular, but trapezoidal.

Because of the plastic deformation, some material is stored on the extreme sections (Z = −5 mm and Z = −15 mm), the corresponding diameter of the pin enlarges and two small protrusions are visible.

5. Conclusions

Referring to the inspection of sheet metal parts, a specific wear test for the investigation of life time and wear behaviour of tailored AM fixtures of Alumide material was presented in this paper. Since standard tests for wear evaluation are not representative of real wearing conditions of the fixture, a custom tribometer was designed for a specific novel test. The apparatus provides an alternating uniaxial motion to an AM fixture that slides inside a hole located in a sheet metal part. During the test, the hole is constantly kept in contact with the fixture by means of a spring.

The specimen for the wear test was designed with a standard geometry represented by a 20 mm long circular pin of 8 mm in diameter. The wear test length was set to 10 mm centred on the pin height and a sliding speed of 0.60 m/min was used with a contact force of 0.59 N. Wear tests were conducted on a sample specimen of Alumide material that was fabricated by SLS.

Each cycle that is imposed to the AM specimen by the tribometer represents the loading and unloading operations of the sheet metal part on the supporting fixture. In such a way, wear was evaluated in terms of number of inspected components before the fixture should be replaced.

Several wearing cycles were repeated and the pin geometry was measured by a CMM after every 500 cycles. The pin consumption was evaluated on seven diameters evenly spaced every 2 mm over the pin height. The maximum wear limit of the pin diameter was set to 0.10 mm.

The Alumide specimen reached such a limit for a number of wearing cycles between 5,000 and 6,000. Thus, its life time can be conservatively assessed in 5,000 inspected sheet metal parts. The wear behaviour of the specimen pin was also justified and discussed.

The results were also compared to those obtained for another specimen made of AA2024 (an Al-Cu alloy) that was manufactured by traditional machining on a turning machine. Considering the similarity of the wear profiles, it can be stated that the two tested materials have almost the same behaviour.

During the test, the specimens underwent wearing under worse than normal conditions. Because of the action of the spring and the 2 mm play between the pin diameter and the size of the hole, wearing was always applied on the same area of the pin surface. On the contrary, in real use, the fixturing tolerances are tight, so the contact zone between the fixture custom element and the mating feature can vary from inspected part to inspected part. For this reason, the life time of the fixture was underestimated by the specific wear test proposed in this study.

Over the first results presented for one specimen, the wear test will be repeated on other Alumide and AA2024 specimens to take into consideration the material variability. The proposed methodology and research activity has a general applicability and will also be extended to other materials that are available for AM of custom fixtures to compare their durability.

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